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RESEARCH ARTICLE

Dynamic characteristics and drivers of the regional household energy-carbon-water nexus in China

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Abstract

Being a node of the energy-water consumer and carbon dioxide (CO_2) emitter, the household is one key sector to pilot integrated energy-carbon-water (ECW) management. This study developed an integrated framework to explore China's provincial household ECW nexus as well as their drivers from the years 2000 through 2016. The absolute amount and growth rate of household energy use (HEU), household CO_2 emissions (HCE), and household water use (HWU) were abstracted to reveal the dynamic characteristics of the household ECW nexus. Efficiency advance, income growth, urbanization, family size, and household number were defined to explain the changes in the household ECW nexus. This study revealed that there is a huge regional heterogeneity in China's household ECW nexus. Developed regions such as Zhejiang, Jiangsu, Guangdong, and Shanghai are the most important household ECW nexus nodes with larger amounts and growth rates of household ECW. Income growth overwhelmingly increases ECW, while efficiency advance effectively curbs its growth. Comparatively, household number, family size, and urbanization have small effects. Therefore, implementing differentiated management and focusing on the synergy of socioeconomic factors are the keys to achieving integrated household ECW management. And the analytical framework can be used to analyze ECW nexus from a sector, city, or country perspective.

Keywords Dynamic characteristics · Drivers · Energy-carbon-water nexus · Household · China · Regions

Introduction

Energy and water are indispensable inputs to sustain modern economic growth and human survival, and climate change affected by anthropogenic carbon dioxide (CO_2) emissions is a great challenge faced by human (Khalkhali et al. 2018; Li et al. 2019a). The three environmental factors of energy, CO_2 emissions, and water (ECW) are considered as the basic factors influencing socioeconomic sustainability (Yang et al. 2018; Zheng et al. 2019). The signing of the Paris Agreement has put forward more urgent requirements for the United Nations Framework Convention on Climate Change (UNFCCC) member states to strengthen their response to the threat of climate change. Therefore, solving the shortage of one kind of resource (such as energy) without causing other problems (such as water resource shortage and CO_2 emissions

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increase) is the basis of achieving Sustainable Development Goals (SDGs) in the process of mitigating global warming and reducing CO_2 emissions. Energy and water shortage as well as climate change mitigation has attracted worldwide attention and required people to search for an effective solution to integrated ECW management in order to achieve socioeconomic sustainable development.

In China, the ECW issue has increasingly emerged and has become complicated. China has witnessed rapid economic growth and population expansion in the past decades. The extensive and resource-based economic development patterns and subsequently over-exploitation of energy and water resources have resulted in severe energy and water shortages and excessive greenhouse gas (GHG) emissions in China. Ongoing climate change could further increase the uncertainty of the sustainable supply of energy and water resources in China. At the same time, driven by rapid urbanization and soaring consumption, the ECW of China's households has increased considerably; this increase is likely to continue in the expected future (Fan et al. 2019; Liao et al. 2019). Energy-related CO_2 emissions of China's household sector in 2016 were measured at 374 Mt. Households are considered as a primary focus of water management as electrification induces an increasing amount of water use and greatly influences water scarcity (He et al. 2018). However, due to the large individual differences within the household sector, it is difficult to account and manage its ECW, so it inevitably increases the cost of government policy implementation. Can we try to track the ECW of China's households? What are the drivers for changes in household ECW? How to realize the integrated management of household ECW? To solve the above problems is helpful for policymakers to formulate integrated environment management policies, and can provide solutions for the realization of sustainable development from the perspective of household sector.

There exists an extremely complex relationship among the elements of ECW—in other words, the ECW nexus (Scott et al. 2011; Chhipi-Shrestha et al. 2017). Existing studies show that the ECW nexus is further explored in terms of the quantities of national, regional, urban, and sectoral ECW as well as the trade-offs, spillover effects, synergies, and co-benefits of various ECW-related measures (Zhou et al. 2016; Chhipi-Shrestha et al. 2018). Ali et al. (2019) used the multi-criteria decision analysis (MCDA) method and the Bilan Carbone model to predict future energy demand and CO_2 emissions of Lahore Metropolitan Area (LMA) in Pakistan. Chhipi-Shrestha et al. (2017) revealed the highly significant interconnections between ECW by calculating the Spearman's correlation coefficients. Some scholars have evaluated the characteristics of ECW from the national and urban levels (Yang et al. 2018, 2019; Lee et al. 2021), and many studies analyzed the application of ECW in sectors. Maupin et al. (2014) found that the proportion of water use for thermoelectric power generation accounted for 45% in the USA in 2010. Ali et al. (2017) and Tantisattayakul et al. (2016) found that the total annual CO_2 emission of Bangkok is about 45.8 Mtoe, and the transportation sector is the main contributor. Li et al. (2020) found that the agricultural sector has gradually become an ECW intensive sector.

Additionally, Chen and Chen (2017) emphasized the dynamic nature of the nexus. They also pointed out that socio-economic factors have been incorporated into the urban nexus paradigm, and many studies have evaluated the effects of how these factors impacted the urban development from a nexus perspective. To date, the implication of the ECW nexus has been extended as the dynamic ECW interrelationship, including the interdependency among the elements of ECW and the effects of socioeconomic factors and ECW-related policies (or measures) on ECW.

Most existing studies focus on assessing the dynamic impact of ECW-related policies. Scholars found that if renewable energy was used to replace the existing thermal-dominated power generation, many countries can significantly reduce CO_2 emissions and water use (Arent et al. 2014). Xu and Lin (2019) found that the expansion of natural gas consumption has different effects on CO_2 emissions in different regions. Stokes et al. (2014) found that water pricing system was more cost-effective than emission trading schemes (ETS) in reducing GHG emissions. Research on the dynamic effects of socioeconomic factors on ECW is blank, although some studies have evaluated the dynamic effects of socioeconomic factors on energy, carbon emissions, or water, such as urban size (Chen and Chen 2017; Ali et al. 2018), trade (Nawab et al. 2019), and industrial structure adjustment (Lee et al. 2021). Therefore, considering the complicated relationships of the ECW nexus, uncovering their intrinsic relations and drivers along with socioeconomic development helps to offer insights into the integrated ECW management of China.

At present, many methods have been used to study ECW nexus. Top-down and bottom-up methods are the most commonly used (Wang et al. 2017). The top-down method uses input-output (IO) analysis (Yang et al. 2018), system dynamic (SD) model (Feng et al. 2016), and CGE model (Zhou et al. 2016) to evaluate. However, IO analysis can only carry out material flow accounting and cannot directly evaluate the effects of socioeconomic factors. When the model complexity is high, SD model will produce chaos and bifurcation problems (Feng et al. 2016). CGE model cannot accurately describe the differences of ECW mechanism among different sectors, and a large number of parameter assumptions increase the complexity and uncertainty (Li et al. 2019a). At the same time, the bottom-up method generally uses the principle of life cycle assessment (LCA) to investigate ECW (Dodder et al. 2016). However, LCA has high data requirements and cannot accurately evaluate the system boundary, which may lead to poor accuracy of the results.

In addition, other methods are also used to analyze ECW nexus, such as structural decomposition analysis (SDA) and logarithmic mean Divisia index (LMDI) decomposition. Compared with SDA, LMDI method has more diverse decomposition forms and simpler data requirements. Therefore, LMDI method is considered to be the best method to quantify effects of various socioeconomic factors on ECW nexus (Li et al. 2019a). In recent years, scholars use LMDI method to explore the driving factors of energy consumption (Li et al. 2019a), CO_2 emissions (Chen and Zhu 2019), and water use (Zhang et al. 2019) from the national, urban, and sectoral perspectives. Therefore, in consideration of the advantages of LMDI method, this study uses LMDI method to evaluate the dynamic characteristics and drivers of the regional household ECW nexus in China so as to provide decision-making references for integrated management of household ECW.

The present study enriches the existing literature in two ways. Firstly, to our best knowledge, this is the first study analyzing ECW nexus of China's household sector from a dynamic perspective, which caters dynamic nature of nexus. Secondly, socioeconomic factors such as family size and household number are introduced to explore their effects on ECW nexus of household sector. The integrated analytical framework for ECW nexus of household sector is developed, and this expands the application of LMDI decomposition method. The findings could provide a reference for policymakers to design integrated management policies of household ECW and help to achieve sustainable economic and social development.

The rest of this study is organized as follows. The "Method and data source" section discusses the model framework, decomposition model, and data source, and the "Dynamic characteristics of the regional household ECW nexus in China" section introduces the ECW nexus characteristics. Then the contributions of various driving factors are assessed in the "Driving analysis of the ECW nexus" section. Lastly, the "Conclusions and implications" section draws the main conclusions and policy recommendations of this study.

Method and data source

Model framework

The integrated analytical framework is illustrated in Fig. A1.

Indicator selection of the household ECW nexus characteristics

Existing studies selected or established the indicators to uncover the characteristics of the ECW nexus. The most widely used indicators to measure the ECW nexus include the direct or embodied ECW of a sector (or an economy) and ECW flows between sectors (or economies) (Li et al. 2019b; Zhang et al. 2019). The increment of ECW was employed in our previous study (Li et al. 2019a). In addition, some indicators, such as Spearman's rank correlation coefficients and the consumption (emission) index were established to analyze the ECW nexus (Chhipi-Shrestha et al. 2017; Yang et al. 2018). In this study, we choose both the absolute amount and the increments of HEU, HCE, and HWU to represent household ECW nexus characteristics.

Decomposition model of dynamic change of the household ECW nexus

The improved LMDI method is applied in order to decompose the changes of HEU, HCE, and HWU into an energy/carbon/water intensity effect, income improvement effect, urbanization effect, family size effect, and a household number effect. The dimensionless contribution degrees of various factors to the changes of HEU, HCE, and HWU are integrated to uncover their impacts on the household ECW nexus. Then, the major driving factors to the household ECW nexus are identified. Finally, discussions are made for in-depth findings, and accordingly, policy implications are offered.

Decomposition model

LMDI method was proposed by Ang (2004) on the basis of Kaya identity. Compared with other decomposition methods, LMDI has the characteristics of complete decomposition, no residual, and unique result, so it is widely used in the field of energy economics. In this study, the original Kaya identity is improved, and the improved LMDI method is obtained by including family size, household number, and other drivers into the decomposition model. The relationships among HEU, energy intensity, income level, urbanization, family size, and household number in region i of China ($i = 1, 2, \cdots, 30$) are described in Eq. (1), where j denotes urban and rural household sectors. Notably, the definitions of all of the variables used in this study are displayed in Table A.1.

$$E_i = \sum_{j=1}^{2} E_{ij} = \sum_{j=1}^{2} \frac{E_{ij}}{Y_{ij}} \cdot \frac{Y_{ij}}{P_{ij}} \cdot \frac{P_{ij}}{P_i} \cdot \frac{P_i}{H_i} \cdot H_i = \sum_{j=1}^{2} EI_{ij} \cdot \mathrm{AVY}_{ij} \cdot U_i \cdot F_i \cdot H_i \quad (1)$$

The change of household energy use in region i could be decomposed into an energy intensity effect, income improvement effect, urbanization effect, family size effect, and a household number effect as shown in Eq. (2). The effects of various factors could be calculated through Eqs. (3)–(7).

$$\Delta E_{i,\text{total}}^{(T-0)} = E_i^T - E_i^0 = \Delta E_{i,EI}^{(T-0)} + \Delta E_{i,Y}^{(T-0)} + \Delta E_{i,U}^{(T-0)} + \Delta E_{i,F}^{(T-0)} + \Delta E_{i,H}^{(T-0)} \quad (2)$$

$$\Delta E_{i,\mathrm{EI}}^{(T-0)} = \sum_{j=1}^{2} L\left(E_{ij}^{T}, E_{ij}^{0}\right)\cdot\ln\left(\frac{\mathrm{EI}_{ij}^{T}}{\mathrm{EI}_{ij}^{0}}\right) \quad (3)$$

$$\Delta E_{i,Y}^{(T-0)} = \sum_{j=1}^{2} L\left(E_{ij}^{T}, E_{ij}^{0}\right)\cdot\ln\left(\frac{Y_{ij}^{T}}{Y_{ij}^{0}}\right) \quad (4)$$

$$\Delta E_{i,U}^{(T-0)} = \sum_{j=1}^{2} L\left(E_{ij}^{T}, E_{ij}^{0}\right)\cdot\ln\left(\frac{U_{ij}^{T}}{U_{ij}^{0}}\right) \quad (5)$$

$$\Delta E_{i,\mathrm{F}}^{(T-0)} = \sum_{j=1}^{2} L\left(E_{ij}^{T}, E_{ij}^{0}\right)\cdot\ln\left(\frac{F_{i}^{T}}{F_{i}^{0}}\right) \quad (6)$$

$$\Delta E_{i,H}^{(T-0)} = \sum_{j=1}^{2} L\left(E_{ij}^{T}, E_{ij}^{0}\right)\cdot\ln\left(\frac{H_{i}^{T}}{H_{i}^{0}}\right) \quad (7)$$

The contribution degrees of various factors are calculated by dividing the effect by total change of HEU of region i, as showed in Eqs. (8)–(12).

$$\Delta \mathrm{EC}_{i,\mathrm{EI}}^{(T-0)} = \Delta E_{i,\mathrm{EI}}^{(T-0)} / \Delta E_{i,\mathrm{total}}^{(T-0)} \quad (8)$$

$$\Delta \mathrm{EC}_{i,Y}^{(T-0)} = \Delta E_{i,Y}^{(T-0)} / \Delta E_{i,\mathrm{total}}^{(T-0)} \quad (9)$$

$$\Delta \mathrm{EC}_{i,U}^{(T-0)} = \Delta E_{i,U}^{(T-0)} / \Delta E_{i,\mathrm{total}}^{(T-0)} \quad (10)$$

$$\Delta \mathrm{EC}_{i,F}^{(T-0)} = \Delta E_{i,F}^{(T-0)} / \Delta E_{i,\mathrm{total}}^{(T-0)} \quad (11)$$

$$\Delta \mathrm{EC}_{i,H}^{(T-0)} = \Delta E_{i,H}^{(T-0)} / \Delta E_{i,\mathrm{total}}^{(T-0)} \quad (12)$$

Similarly, the changes of CO_2 emissions and water use of region i could be decomposed as Eqs. (13)–(16), and the effects and contribution degrees of various factors to HCE and HWU are quantified similar to that of HEU.

$$C_i = \sum_{j=1}^{2} C_{ij} = \sum_{j=1}^{2} \frac{C_{ij}}{Y_{ij}}\cdot\frac{Y_{ij}}{P_{ij}}\cdot\frac{P_{ij}}{P_i}\cdot\frac{P_i}{H_i}\cdot H_i = \sum_{j=1}^{2} CI_{ij}\cdot \mathrm{AVY}_{ij}\cdot U_i\cdot F_i\cdot P_i \quad (13)$$

$$\Delta C_{i,\mathrm{total}}^{(T-0)} = C_i^T - C_i^0 = \Delta C_{i,CI}^{(T-0)} + \Delta C_{i,Y}^{(T-0)} + \Delta C_{i,U}^{(T-0)} + \Delta C_{i,F}^{(T-0)} + +\Delta C_{i,H}^{(T-0)} \quad (14)$$

$$W_i = \sum_{j=1}^{2} W_{ij} = \sum_{j=1}^{2} \frac{W_{ij}}{Y_{ij}}\cdot\frac{Y_{ij}}{P_{ij}}\cdot\frac{P_{ij}}{P_i}\cdot\frac{P_i}{H_i}\cdot H_i = \sum_{j=1}^{2} \mathrm{WI}_{ij}\cdot \mathrm{AVY}_{ij}\cdot U_i\cdot F_i\cdot P_i \quad (15)$$

$$\Delta W_{i,\mathrm{total}}^{(T-0)} = W_i^T - W_i^0 = \Delta W_{i,WI}^{(T-0)} + \Delta W_{i,Y}^{(T-0)} + \Delta W_{i,U}^{(T-0)} + \Delta W_{i,F}^{(T-0)} + \Delta W_{i,H}^{(T-0)} \quad (16)$$

Then, the contribution degree of each socioeconomic factor to HEU, HCE, and HWU are integrated to reveal their effect on the household ECW nexus. For example, $\Delta \mathrm{ECW}_{i,I}^{(T-0)} = \left(\Delta \mathrm{EC}_{i,\mathrm{EI}}^{(T-0)}, \Delta \mathrm{CC}_{i,\mathrm{CI}}^{(T-0)}, \Delta \mathrm{WC}_{i,\mathrm{WI}}^{(T-0)}\right)$ indicates the effects of efficiency advance which includes energy efficiency advance, carbon efficiency advance, and water efficiency advance on the household ECW nexus of region$i$; $\Delta \mathrm{ECW}_{i,H}^{(T-0)} = \left(\Delta \mathrm{EC}_{i,H}^{(T-0)}, \Delta \mathrm{CC}_{i,H}^{(T-0)}, \Delta \mathrm{WC}_{i,H}^{(T-0)}\right)$ indicates the effects of the household number effect (i.e., household expansion) on the household ECW nexus.

Data sources

The data regarding the HEU and HCE of the various regions from 2000 through 2015 comes from Shan et al. (2016, 2018). In order to maintain data caliber consistency, the growth rates of the HEU and HCE of various regions are first calculated according to the HEU data from 2015 to 2016 collected from the energy balance sheet. The urban and rural HEU in 2016 are then calculated based on the HEU data from 2015 from the China Emission Accounts and Datasets (CEADs, 2015) and the growth rates from 2015 to 2016 from the energy balance sheet. The HCE in 2016 of various regions were calculated by using the similar method for HEU. The HWU of various regions from period of 2000 through 2016 were collected from the China Environmental Yearbook. Data of disposable income, population, and family size were derived from the China Statistical Yearbook. Household disposable incomes were deflated through the annual Consumer Price Index (CPI) from 2000 through 2016. Households were calculated through dividing regional populations by family size.

Dynamic characteristics of the regional household ECW nexus in China

Regional household energy use, CO_2 emissions, and water use

Figure 1 shows the HEU, HCE, and HWU of China by region in 2000 and 2016. HEU of various regions in China varied significantly, and HEU in the eastern region is significantly higher, as shown in Fig. 1. For example, the HEU of five eastern provinces ranked in the top 25% of all provinces in 2016. Guangdong contributed most of the 34.2 million tons of coal equivalent (Mtce) to national HEU; this was followed by Hebei (25.0 Mtce) and Shandong (20.8 Mtce). Jiangsu, Zhejiang, Beijing, and Shanghai all ranked in the top 50% for HEU. In contrast, the central and western regions have lower HEU, with most of them below average. However, Hunan (21.1 Mtce) is an exception, ranking the third in China. Henan (14.6 Mtce), Sichuan (13.3 Mtce), and Hubei (13.1 Mtce) also showed high HEU. The household sector of Ningxia only consumed 1.36 Mtce of energy resources in 2016, ranking last. Hainan (1.4 Mtce) and Qinghai (2.0 Mtce) also showed lower HEU. During the period of 2000 through 2016, most central and eastern regions experienced

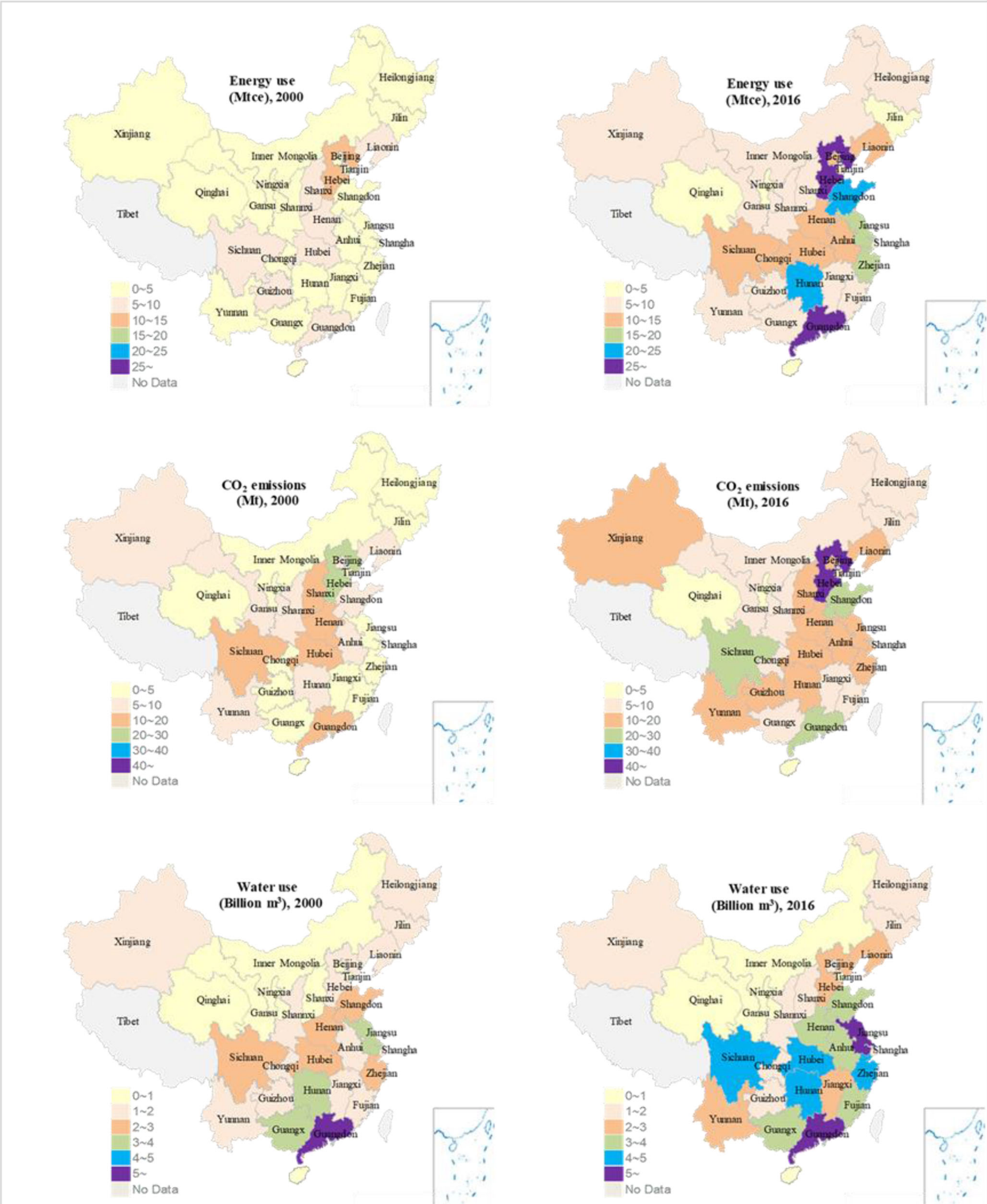

Fig. 1 Regional heterogeneity of HEU, HCE, and HWU in 2000 and 2016

a significant increase of above 300%, especially in Hunan (583.2%), Anhui (435.0%), and Jiangsu (418.6%), while the growth of HEU in Guizhou (35.0%) and Gansu (85.2%) were relatively slight. In summary, the regional household sector shares the similar characteristics of considerable HEU, rapid growth, and regional inequity.

The regional characteristics of HCE were roughly the same to HEU because HCE were directly emitted by HEU. HCE was significantly higher in eastern regions, and the eastern provinces with higher HEU tended to have higher HCE. Hebei ranked first in HCU with 42.0 million tons (Mt) among the regions in 2016; Shandong (29.3 Mt) and Guangdong (28.5 Mt) followed. Sichuan (22.7 Mt) and Hunan (18.6 Mt), located in central and western regions, had higher HCE. Interestingly, Qinghai (3.3 Mt), Ningxia (2.2 Mt), and Hainan (1.4 Mt) also ranked in the bottom three. The research results of Xu and Lin (2020) also show that there are differences in energy consumption structure among provinces, so the energy consumption and carbon emissions are different among different provinces. Various regions were observed to have large heterogeneity and a rapid rise in HCE over the past two decades. However, the growth rates of HCE in various regions were lower than that of HEU from the years 2000 through 2016 mainly because the improvements in both energy structure and energy efficiency brought forth the increase in HEU.

As can be seen from Fig. 1, the eastern, central, and southern regions tended to have large HWU. Guangdong had the largest HWU with 8.7 billion m^3 in 2016, followed by Jiangsu with 5.1 billion m^3. Hubei (4.9 billion m^3), Sichuan (4.7 billion m^3), Hunan (4.3 billion m^3), and Zhejiang (4.3 billion m^3) also had higher HWU than other regions. It is worth noting that Tianjin, located in the eastern region, ranked third from the bottom in 2016 with HWU of 0.5 billion m^3. Northern regions, such as Inner Mongolia (0.9 billion m^3), Gansu (0.8 billion m^3), Qinghai (0.3 billion m^3), and Ningxia (0.2 billion m^3), had lower HWU than the eastern and southern regions due to their scarce water resources, lower incomes, and sparse populations. The growth rates of HWU in most regions were quite significant during the period of 2000 through 2016 while lower than that of corresponding regional HEU and HCE. However, there was a larger growth rate of HWU in Sichuan than HEU. This could be attributed to the fact that Sichuan, a water-rich region, had employed a large amount of water resource to generate electricity for meeting its regional energy demands.

Regional household ECW nexus in terms of ECW growth rate

The changes of HEU, HCE, and HWU, represented by their growth rates, are also adopted to reveal the characteristics of the household ECW nexus. There were similar growth trends in terms of HEU, HCE, or HWU in most of the regions during the period from 2000 through 2016; the regions with higher (or lower) growth rates of HEU had higher (or lower) growth rates of HCE and HWU. As shown in Fig. 2, the economically developed regions—especially Jiangsu and Zhejiang—experienced sharp increases in household ECW from 2000 through 2016. Due to a pleasant climate and comfortable environment, Hainan had attracted a large inflow of immigrants during the past decades, which then led to a dramatic increase of HEU, HCE, and HWU. Besides, the soaring tourism industry of Hainan improved household income and further increased household ECW. In 2016, Hainan ranked second in population growth, next to Shandong. However, HEU, HCE, and HWU in the economically developing central and western regions increased slightly compared with that of the developed regions. Another important phenomenon is that the growth rate of HEU is faster than that of HEU in most regions. Notably, energy-intensive regions, such as Shanxi, Ningxia, and Xinjiang, showed relatively lower growth rankings of HEU than HWU.

Integrated analysis of the regional household ECW nexus characteristics

The characteristics of the household ECW nexus could be further analyzed through integrating their quantities and growth rates. The regions could be divided into five categories according to their scores of both absolute quantity and relative growth rate of household ECW.

As shown in Table 1, Zhejiang, Jiangsu, Guangdong, Shanghai, and Anhui have both larger quantity and growth of household ECW from 2000 through 2016. These economically developed regions—except Anhui—could be regarded as the most important household ECW nexus regions in China, and more attention should be paid to these regions for integrated ECW management.

Developing western regions, such as Gansu, Ningxia, and Xinjiang, have both smaller quantities and growth rates of their household ECW from the years 2000 through 2016. Accordingly, these regions should focus more on economic development and ECW efficiency advance.

The regions with relatively smaller quantity of but higher growth rate of household ECW could be classified as the third category. These regions, including Beijing, Tianjin, Chongqing, and Hainan, tend to have rapid income growth and large inflows of labor and thus have significant increases in their household ECW.

The fourth category refers to the regions with higher quantities or growth rates of HEU and ECW but lower quantities or growth rates of HWU during the period of 2000 through 2016. Most of these regions, such as Inner Mongolia, Heilongjiang, and Shandong, are located in energy-rich but water-deficient North or Northwestern China and could pay more attention to their energy resource management and emission reduction.

The fifth category regions have relatively higher quantities or growth rates of household HWU along with lower quantities or growth rates of household HEU and ECW. These tend to be the southern water-rich but energy-deficient regions,

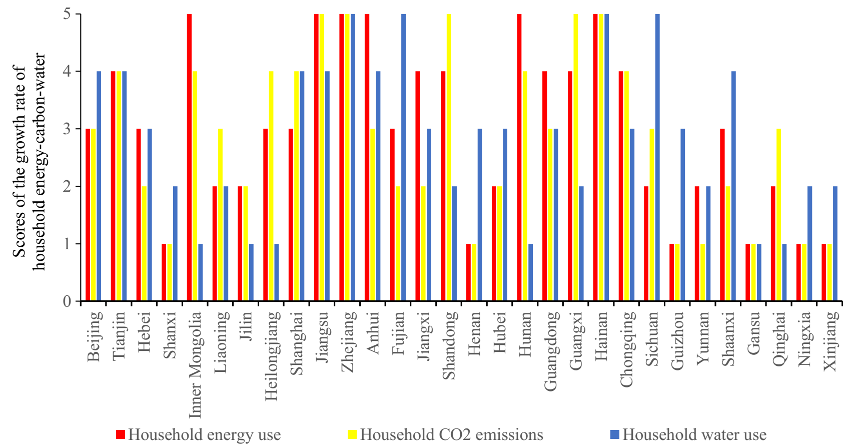

Fig. 2 The household ECW nexus in terms of its growth rate in various regions

such as Guizhou and Sichuan, and effective water resources management is more urgent in these areas.

Driving analysis of the ECW nexus

Overall effects of various socioeconomic factors on HEU, HCE, and HWU in China

Effects of various socioeconomic factors on HEU

As shown in Fig. 3, the effects of various socioeconomic factors on HEU differed significantly among regions from the years 2000 through 2016. In view of the effects of various factors, income improvement effect played a dominating role in increasing regional HEU from 2000 through 2016. Income improvement in Hebei promoted its increase of HEU by 19.7 Mtce, followed by Henan (14.7 Mtce) and Shandong (14.2 Mtce), Guangdong (12.1 Mtce), Sichuan (12.0 Mtce), Jiangsu (11.6 Mtce), and Zhejiang (10.8 Mtce). Shandong, Guangdong, Jiangsu, and Zhejiang are economically developed and high-income regions in China. The energy intensity effect was the most important factor to curb the increase in regional HEU. A larger energy intensity effect occurred in Henan (−9.3 Mtce), Guizhou (−8.3 Mtce), and Guangdong (−8.1 Mtce). Household number effect played another important role in the increase of regional HEU. Populous and economically developed regions would have larger household number effects from 2000 through 2016. Beijing and Shanghai ranked first and second in their growth rates of permanent populations among regions after 2000. Also, resource-intensive regions, such as Shanxi, Guizhou, and Xinjiang, attracted many laborers for resource development, which was driven by the Western Development Strategy (Mi et al. 2017). Family size effect reduced HEU because of gradual family miniaturization in China. Thanks to this family planning policy, persons per household decreased in various regions. The decline of persons per household directly reduced energy use per household. The largest effect of family miniaturization during the period from 2000 through 2016 occurred in Shanxi (−1.9 Mtce), Hubei (−1.9 Mtce), Sichuan (−1.8 Mtce), and Guizhou (−1.8 Mtce). The effects of urbanization varied among regions.

Table 1 Key household ECW nexus regions in China

Region	Household ECW nexus	
	Quantity	Growth
Shanghai	(3, 3, 3)	(3, 4, 4)
Jiangsu	(5, 5, 4)	(5, 5, 4)
Zhejiang	(5, 5, 5)	(5, 5, 5)
Anhui	(4, 3, 4)	(5, 3, 4)
Guangdong	(5, 5, 5)	(4, 3, 3)

Effects of various socioeconomic factors on HCE

As shown in Fig. 4, the effect of income improvement and household number played an important role in the increase of regional HCE, and the effect of carbon intensity was the dominant factor for the decrease of regional HCE from the years 2000 through 2016. Specifically, Hebei attained the largest increase in HEU but ranked third in HCE (16.7 Mt) from 2000 to 2016, next to Shandong (23.0 Mt) and Guangdong (17.2 Mt). The carbon intensity effect in Hebei attributed most of its 26.6 Mt to the reduction of its HCE during the period of 2000 to 2016, followed by Henan (−21.3 Mt), Shanxi (−16.7 Mt), and Xinjiang (−14.7 Mt). These larger inhibitory effects were attributed to the improvement of both energy technology and energy structure. Hebei, due to its lower urbanization rate and household income, consumed a large amount of bulk coal, straw, and firewood for household space heating and cooking in the last decades. In recent years, households in Hebei have been experiencing a rapid transition toward clean energy from coal to electricity and to natural gas. There has also been a large-scale development of renewable energy and a significant

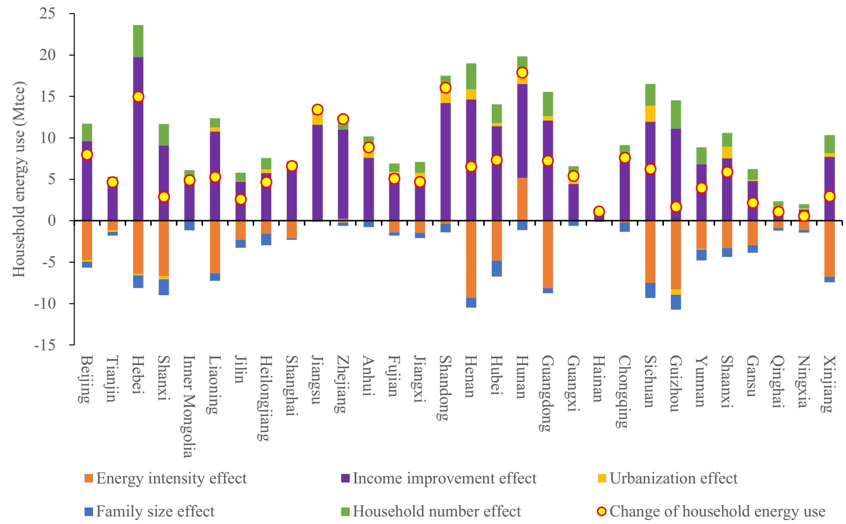

Fig. 3 Effects of various socioeconomic factors on household energy use from 2000 to 2016

improvement of energy efficiency through promoting energy-saving appliances and central space heating. These measures effectively restrained the increase of HCE in Hebei from 2000 to 2016. Shanxi and Xinjiang, as important fossil energy bases, significantly improved their household energy structure and energy efficiency. As a result of their rapidly decreasing fossil energy reserve and the promotion of energy transition in Shanxi and Xinjiang, their coal-dominated energy structure has been optimized with an increasing share of electricity and natural gas consumption in the household sector. As the most developed regions, Beijing and Shanghai have implemented the energy policy of "reducing coal, diverting electricity, increasing gas, and using new energy" and outsourced electricity and natural gas accounted for a larger share in total HEU.

Effects of various socioeconomic factors on HWU

Income improvement effect and water intensity effect were the major positive and negative driving factors of HWU in various regions during the period of 2000 through 2016, respectively (shown in Fig. 5). However, the effects of each factor on HWU were different from that of HEU and HCE.

The income improvement effect on HWU reached 8.0 billion cubic meters (m^3) in Guangdong from 2000 to 2016, which is far greater than Hunan (5.10 billion m^3) and Jiangsu (5.0 billion m^3). This larger income improvement effect on HWU also appeared in Guangxi, Zhejiang, Sichuan, Henan, and Hubei. The water intensity effect mostly offset the increase of HWU in most regions and effectively restrained the increase of HWU from 2000 through 2016. The absolute

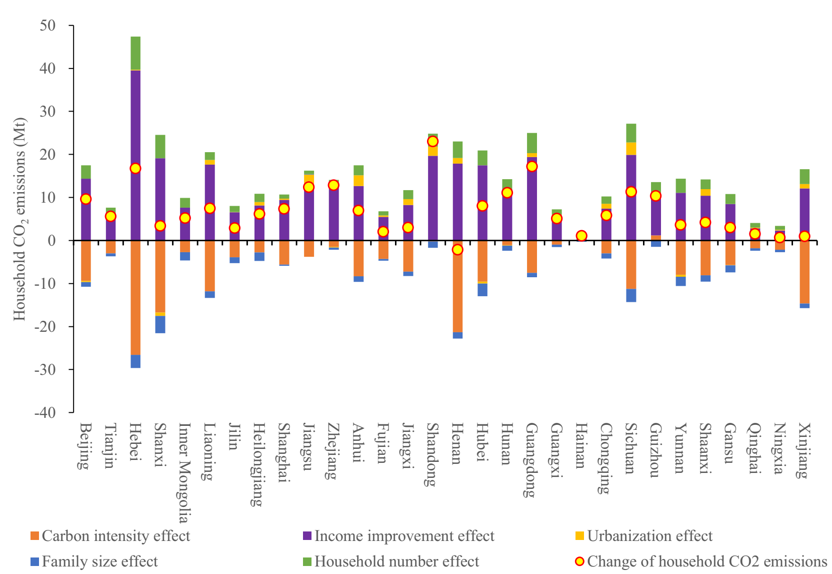

Fig. 4 Effects of various socioeconomic factors on household CO_2 emissions from 2000 to 2016

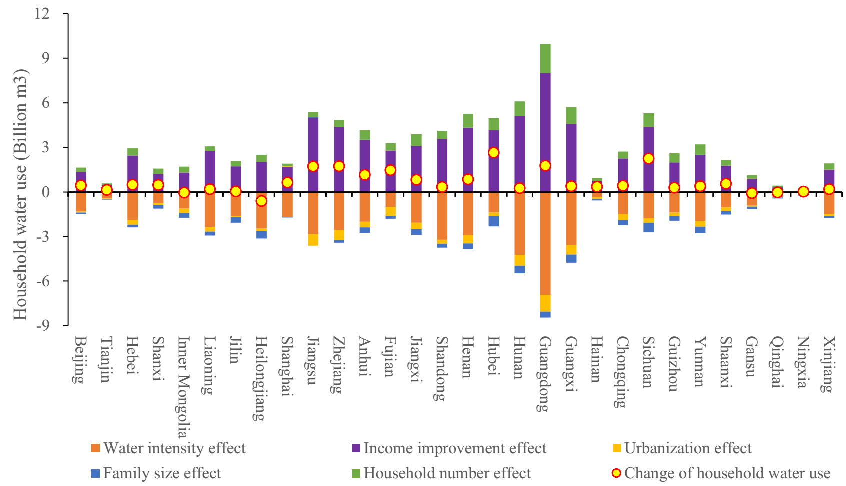

Fig. 5 Effects of various socioeconomic factors on household water use from 2000 to 2016

value of the water intensity effect was approximately equal to that of the income improvement effect in most regions. However, in water-rich regions, the water intensity effect only offset part of the income improvement effect, and thus HWU increased sharply from 2000 to 2016. For example, Jiangsu and Zhejiang had a water intensity effect of −2.8 billion m^3 and −2.6 billion m^3, respectively, only offsetting part of their income improvement effects of 5.0 billion m^3 and 5.0 billion m^3. Water-deficient regions made greater achievements in water efficiency advance than water-rich regions, while water-rich regions may pay relatively less attention to the reduction of HWU. Household number effect played another important role in increasing regional HWU. Guangdong had the largest household number effect of 1.9 billion m^3 among the regions. Larger household number effect mainly occurred in the southern regions, such as Hubei, Hunan, and Sichuan. Henan achieved a larger household number effect because of its large increase in its population. Family size effect was negative in most regions except Jiangsu. Developing regions have a larger family size effect because they effectively reduced their persons per household compared with the developed regions. Urbanization effect was negative in most regions. This could be attributed to water efficiency advance due to central water supply, the promotion of water-saving sanitary ware, rising water-saving consciousness, and the improvement of water pricing mechanisms.

Contributions of various socioeconomic factors to the household ECW nexus

General characteristics in terms of the contributions of socioeconomic factors to the household ECW nexus

Generally, as shown in Fig. 6, various socioeconomic factors showed a synergic effect on regional HEU, HCE, and HWU (i.e., household ECW). Both efficiency advance and family miniaturization would reduce HEU, HCE, and HWU in most regions. Energy and water were simultaneously used for cooking and water heating. HWU reduction could also have led to the decline of HEU and HCE. For example, family miniaturization led to the reduction of HEU by 10.3%, of HCE by 18.4%, and HWU by 39.8% in Hebei during the period from 2000 through 2016; accordingly, efficiency advance reduced its HEU by 43.0%, HCE by 158.7%, and HWU by 388.5%. In contrast, income improvement and household expansion would increase HEU, HCE, and HWU. High-quality lifestyles would be accompanied by delicious dishes with complex cooking processes and frequent washing (such as laundry and shower) that consumed more energy and water resources. For example, income improvement increased Shandong's HEU by 88.5%, HCE by 85.4%, and HWU by 1029.8%, and household expansion increased its HEU by 13.4%, HCE by 12.9%, and HWU by 158.8%.

Contributions of each factor to HEU and HCE from the years 2000 through 2016 were close, while they greatly differed with regard to HWU. There was a greater contribution of each factor to HWU than HEU and HCE in most regions. In other words, HWU was more sensitive to the changes caused by socioeconomic factors; socioeconomic development would produce larger effects on HWU than HEU and HCE for most regions. For example, in Beijing, contributions of efficiency advance, income improvement, urbanization, family miniaturization, and household expansion to HWU during the period from 2000 through 2016 were −59.5%, 120.4%, −2.4%, −8.8%, and 26.1%, while to HEU they were −303.5%, 310.3%, −15.0%, −23.0%, and 68.1%, respectively.

Income improvement and efficiency advance contributed much more to HWU than to HEU. Along with the improvement of household income, large amounts of water resources were consumed for cooking, laundering, and showering, but HEU would limitedly increase if solar heaters were introduced. Stakeholders could pay more attention to water resource management, such as the implementation of Three Red Lines water policy, because water resources could play


Beijing
Tianjin
Hebei
Shanxi
Inner Mongolia
Liaoning
Jilin
Heilongjiang
Shanghai
Jiangsu
Zhejiang
Anhui
Fujian
Jiangxi
Shandong
Henan
Hubei
Hunan
Guangdong
Guangxi
Hainan
Chongqing
Sichuan
Guizhou
Yunnan
Shaanxi
Gansu
Qinghai
Ningxia
Xinjiang
ΔECW_I
ΔECW_Y
ΔECW_U
ΔECW_F
ΔECW_H
Contribution to HEU (%)
Contribution to HCE (%)
Contribution to HWU (%)

◀ **Fig. 6** Contributions of various factors on household energy-carbon-water nexus from 2000 to 2016**.** Note: ΔECW_I, ΔECW_Y, ΔECW_U, ΔECW_F, and ΔECW_H indicate the contribution degrees of efficiency advance, income improvement, urbanization, family miniaturization, and household number expansion to household ECW

a more crucial role in household daily life. Therefore, various regions achieved greater success in water-saving than in energy-saving and emission-reduction from efficiency advance. Contributions of household expansion, family miniaturization, and urbanization to HEU were relatively close to that of HCE and HWU although their absolute effects on HWU were bigger than HEU and HCE. Marginal increments of HWU for drinking, cooking, and washing were bigger than for HEU and HCE when a person joined or left a family, while marginal increments of HEU and HCE for space heating, space cooling, and cooking could be limited.

In addition, developing and water-deficient regions, such as Inner Mongolia, Jilin, Liaoning, Henan, Hunan, Guangxi, Gansu, Qinghai, and Xinjiang, had larger differences in terms of the contributions of socioeconomic factors to HEU, HCE, and HWU. This was attributed to their higher sensitivity to water use than energy use and CO_2 emissions when socioeconomic factors changed.

The contributions of each socioeconomic factor to the household ECW nexus

In most regions, income improvement played the dominating role in the increase of household ECW, while efficiency advance effectively curbed its increase from 2000 through 2016. Absolute contribution degrees of income improvement and efficiency advance were far greater than that of household expansion, family miniaturization, and urbanization. However, the positive contributions from income improvement were almost offset by negative contributions from efficiency advance. In this case, the growth rate of HEU was smaller than that of HWU in various regions during the period from 2000 through 2016. Developing western and southern regions, such as Guangxi, Yunnan, Inner Mongolia, Gansu, Qinghai, Ningxia, and Xinjiang, tended to have larger contributions of income improvement to household ECW because they have experienced significant income improvements, differing from the eastern regions—especially since the global financial crisis. This phenomenon has been established in the study by Mi et al. (2017) which proved that some economically less-developed regions have shifted from being a net emission exporter to being a net emission importer, mainly due to the changes in consumption structure and the level of consumption per capita. In contrast, developed regions have smaller contributions of income improvement because their growth rate of household ECW declined in the past decades along with income improvement. This could be explained by the small income elasticity of energy and water use and the inverted U-shaped environmental Kuznets Curve.

Northwest regions, such as Xinjiang, Ningxia, Gansu, and Qinghai, achieved greater efficiency improvement of their household ECW when compared to the other regions; they also posed larger contributions of efficiency improvement to household ECW. The water-rich regions of southern China displayed larger contribution degrees of efficiency improvement to HWU, while the north and northeast regions had larger contribution degrees to HEU and HCE. Notably, the southeast and coastal regions had smaller contribution degrees of efficiency improvement to household ECW because these developed regions with higher efficiency had a relatively small reduction potential and higher marginal reduction costs of household ECW than the developing regions.

Household expansion and family miniaturization were another two important factors influencing the increase and decrease of household ECW, respectively. The less developed northwest and southwest regions were observed to have a bigger contribution of household expansion. This was attributed to the larger increase in household numbers promoted by the Western Development Strategy and the Belt and Road Initiative where a large number of laborers transferred to the western regions in search of jobs. The most developed regions in China, such as Beijing, Shanghai, Jiangsu, and Zhejiang, had extremely small contributions to household expansion to household ECW because current household registration systems and higher living costs strictly curbed the inflow of the labor force during these years. Before the study period, these developed regions also had smaller family sizes due to the extremely strict family planning policy, and therefore, the contributions of family miniaturization were smaller than the less developed regions.

Contributions of urbanization were relatively small and varied among regions and among household ECW. Trade-offs existed in terms of the contributions of urbanization on household ECW. Urbanization reduces regional HWU. That was—in the process of urbanization—the reduced HWU from efficiency advance of urbanization which exceeded the increased HWU from the scaled expansion of urbanization. However, in most regions, urbanization increases HEU and HCE, which is consistent with Xu and Lin (2017). With the further development of urbanization, the change of urban and rural population structure and the improvement of residents' consumption concept lead to the increase of household HEU and HCE. In most developed regions (e.g., Beijing, Shanghai, and Zhejiang), contributions of urbanization to household ECW were mainly negative because these regions with extremely high urbanization rates paid more attention to improve their ECW efficiency in the study period.

Conclusions and implications

This study analyzes the characteristics of the household ECW nexus and the driving factors of their dynamic changes of China's 30 regions during the period of 2000 to 2016. Most regions showed a uniform changing trend regarding their quantity and growth rate of HEU, HCE, and HWU. Regions with higher HEU and rapid growth rate tended to have a larger quantity and rapid growth rate of HCE and HWU during the period of 2000 through 2016. Various socioeconomic factors showed the synergic effects on HEU, HCE, and HWU in almost all regions. Income improvement played a dominating role in increasing household ECW, while efficiency advance effectively curbed the increase of household ECW. Household expansion also contributed to the increase of household ECW, but family miniaturization was also responsible for restraining household ECW. Urbanization played varying effects on regional household ECW. HWU was more sensitive to the changes of socioeconomic factors and socioeconomic development would produce larger effect on HWU than HEU and HCE for most regions.

Differentiated management is the basis concept to achieve integrated household ECW management. Water use is more sensitive to socioeconomic factors in the household sector, especially in the water-rich regions. In turn, energy-rich regions could more easily achieve energy-savings (Li et al. 2017). More attention should be paid to technical input and efficiency advance for HEU and HCE in energy-rich regions and for HWU in water-rich regions. At the same time, regional cooperation is an important way to achieve integrated household ECW management. Developed regions should take on more responsibilities in order to develop energy- and water-saving appliances and innovate ECW management mechanisms. Saved water could be transferred to the water-scarce regions; saved energy and emission allowances could be allocated to the energy-scarce regions. In addition, synergies and trade-offs of socioeconomic factors do exist for regional HEU, HCE, and HWU. From a macro point of view, the specific measures involved in the future would produce trade-offs among HEU, HCE, and HWU. Therefore, the analytical framework can be used to further analyze ECW nexus from the perspective of sector, city, region, or country in the future.

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Data availability The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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